MAXIM
The Micro Arcsecond X-ray Imaging Mission

Principal Science Goals

Over the past decade, the study of black holes in the Universe has moved from a quest to prove their existence toward making detailed studies of their properties and testing the laws of physics under extreme conditions. A powerful method for undertaking these studies would be direct imaging. The typical size of an event horizon around nearby supermassive black holes is of order microarcseconds- nearly a million times finer than the angular resolution of the Hubble Space Telescope (HST). In the vicinity of the event horizon of a black hole accreting material is often brightest in X-rays. Accretion can create such a high surface brightness in x-rays that even a modest aperture (1 m^2) will yield high quality, exciting images in reasonable integration times (1 day). The MicroArcsecond X-ray Imaging Mission (MAXIM) will provide 0.1 microarcsecond imaging with enough sensitivity at the right bandpass to capture a picture of a black hole and open up its extreme environment to scrutiny.

A naïve calculation would suggest that, for a maximally rotating black hole with mass M_8 ($10^8 M_{Sun}$) at a distance D (Mpc), the angular diameter of the event horizon is given by:

$$\theta_{r_s}(\mu as) = \frac{2M_8}{D}$$

However, the black hole's strong gravity distorts the space around it, creating a lens and magnifying its own image. This increases the apparent size, θ_{app}, of the event horizon by a factor of about 3 above and beyond the naïve calculation. Table 1 lists a few of the candidate supermassive black hole targets for MAXIM.

How can we take a picture of something from which light cannot escape? Material falling onto a black hole in a binary system, or at the center of a galaxy, forms an accretion disk about the

Table 1: A selection of black hole targets for MAXIM.

Target	***Mass*** [$10^8 M_{sun}$]	***Distance*** [Mpc]	θ_{app} [μas]	***Flux*** [photons/sec/m^2]
NGC 4151	0.1	3.5	1.7	600
NGC 5548	0.5	80	0.036	400
NGC 4258	0.3*	8.0	0.24	20
M 87	32*	15	13	3
Cen A	2.0	3.5	3.4	300
MGC–6-30-15	0.2	37	0.03	400
NGC 4594	20	9	13	3
Galactic Center	0.026*	0.008	19	1-10

The distances are calculated assuming a Hubble constant of 65 km/s/Mpc. Accurately determined kinematic black hole masses are denoted by an asterisk. All other black hole masses are estimates based upon reverberation experiments or host galaxy properties. All of these sources are known to possess variable fluxes; we quote a typical value in the 2-10 keV bandpass.

event horizon. The accretion disk is the catalyst for all the subsequent energetic processes that we can observe. An important and ubiquitous process is the formation of a hot corona above this disk, heated by the release of gravitational energy to temperatures of billions of degrees. X-ray radiation, the dominant energy output, provides the primary method for studying the inner accretion disk close to the event horizon. With MAXIM, we will see the black hole in silhouette against hot material as it spirals in close to the event horizon. We will also see the far side of the disk appear severely distorted as the intense gravity field bends the light around the black hole (figure 1).

While MAXIM's image of a black hole will certainly be one of the new century's most spectacular scientific pictures, it will also address leading questions in black hole research. The image will carry spectroscopic information. We will be able to watch how the emitted spectrum changes with time in individual pixels of our high-resolution image. This will constrain the physics of the X-ray emitting disk corona by allowing us to determine, unambiguously, its geometry and time variability. MAXIM will likely be able to map fluorescent line emission across the accretion disk itself. This would directly give us a spatial map of Keplerian motions across the disk plane within the region where the gravity is relativistic, thereby affording us a direct test of strong field General Relativity.

As we look closer, we will be able to examine the "plunging region" in the immediate vicinity of the black hole. This is the region where the accretion disk matter stops orbiting and starts its final plunge into oblivion. Here, many complex physical processes take place. It is probably in the plunging region where the relativistic AGN jets initially take off. While the large scale structures of these jets are targets for today's X-ray, optical, and radio telescopes, their formation processes are still mysterious. If current observations indicating that the bases of the jets are X-ray bright hold, then MAXIM will image the launch point of the jets and chart their progression away from the black hole. We will learn how a jet relates to the black hole spin and the surrounding magnetosphere.

Microarcsecond imaging will revolutionize studies of a number of other astrophysical objects (see figure 2). MAXIM will be able to resolve the parallax of luminous X-ray binaries within the Virgo Cluster- giving us the most solid footing for the Hubble length scale. We will be able to study dust scattering halos of distant AGN and binary star systems. MAXIM will allow us to resolve the structure within X-ray binary orbits. We will also be able to resolve 100 km coronal structure in nearby stars helping us to understand plasmas, flaring, and magnetic fields in coronae. This is only a partial list of the discovery space awaiting MAXIM– as other leaps in capability have shown us we should "expect the unexpected".

As we evolve beyond the capabilities of Chandra we face something of a "desert". The objects we can resolve today have interstellar and intracluster size scales. With such huge extents, the objects appear static and unrelated to the dynamics of their origins. A careful look at Figure 2 shows that as our resolution starts to improve, we can follow jets down close to their point of origin, but that fundamentally new kinds of targets will not be reached until our resolution approaches one milliarcsecond. Then we can image X-rays from "compact" objects where we view the plasma in the spatial and temporal scales of its own creation. At a few milliarcseconds we can watch the plasma stream between the stars of an interacting binary. As we pass below one milliarcsecond we can take images of stellar coronae that rival the early images of the solar corona. At larger distances we will start to resolve the broad line regions of AGNs and the early blast waves of supernovae. As the resolution moves down toward a microarcsecond, the range of interesting objects grows until we reach the ultimate goal of an event horizon. At one tenth of a microarcsecond only the disks of neutron stars and stellar mass black holes still lie significantly beyond our grasp.

MAXIM and MAXIM Pathfinder

A leap of six orders of magnitude is unprecedented in astronomy and calls for some degree of prudence. Not only will we encounter unexpected technical obstacles, the leap might be too large for astronomy, if we do not proceed step by step. We could lose the context of what we are observing. Sometimes it is simply necessary to “dial back” the magnification in order to see the bigger picture. We need some way to observe intermediate scales starting at milliarcseconds.

A natural way to support the improvements in technology and astronomy is to build an intermediate scale instrument. This MAXIM Pathfinder has a convenient coincidence of astronomy and technology. Reaching the sub-milliarcsecond scales, where the scientific return becomes fundamentally new, requires an interferometer baseline of about one meter. This means the optics can all be mounted in a single spacecraft. We can tackle core technology of X-ray interferometry in the Pathfinder step and delay the difficulties of extended arrays for the full mission.

Thus Maxim Pathfinder is a logical steppingstone to the full goal of imaging a black hole. The Pathfinder will have two spacecraft, one with all the grazing optics and one with the detector. At resolution of 100 microarcseconds and with a modest collecting area, Pathfinder will give us the experience base needed for the full mission and provide the scientific context for understanding the images to follow.

Relevance to National Academy Study Reports and National Priorities

The technical challenges and scientific goals of MAXIM are extremely relevant to several National Academy survey (NAS) reports. MAXIM will be the premier instrument to study the extreme gravity field of a black hole. This puts it in an ideal position to address the strong gravity science goals put forth by the NAS *Committee on Gravitational Physics (1999).* In the *NAS Astronomy and Astrophysics Survey Committee (2001)*, technology development for X-ray interferometry is explicitly recommended so that we can make use of black holes as laboratories of extreme physical conditions. The *NAS Committee on Physics of the Universe (2001)* also describes the utility of an X-ray interferometer to unambiguously probe the vicinity of a black hole and test general relativity.

In addition to being relevant to these National Academy survey reports, MAXIM will be an essential tool to address at least two of the NASA SEU theme’s key objectives:
* To explore the ultimate limits of gravity and energy in the Universe.
* To understand the structure of the Universe, from its earliest beginnings to its ultimate fate.

America has always attached significance to exploring the new frontier. This point is made in the *NAS Physics Survey Overview Committee* (2001). Astronomers are often on the forefront of this exploration. MAXIM will take us to an extreme frontier- the event horizon of a black hole. Propelled by MAXIM's resolution, scientists will take the American public on a virtual journey to a black hole. Black holes capture more than light; they also capture our imagination. Black holes represent the most popular category of questions that reach the NASA/GSFC "Ask a High Energy Astronomer" program, with 18% of the questions on this subject–more than one a day in 2001. Fostering this imagination will help our country's children to not only stay in school, but also to get the most out of scientific and technical education so that they can partake in the exploration of this fantastic frontier. In the same way that the Apollo program inspired a generation of engineers and scientists, the MAXIM mission will help excite a new generation.

The Relation of MAXIM to Other NASA and Foreign Missions

MAXIM will build upon the scientific and technical accomplishments of other NASA space science missions. The detection of X-ray emission enabled the discovery of black holes and it remains today a fundamental signature of accreting black holes. Recent results from the ASCA, XMM-Newton, and Chandra missions have revealed relativistically broadened line features that come from so close to the event horizon that a gravitational redshift is observed. The Constellation-X mission, to be launched in 2010, is optimized to study the iron K line feature discovered by ASCA and will determine the black hole mass and spin for a large number of systems. This will provide an indirect measure of the properties of the region within a few black hole radii of the event horizon.

The technology to build MAXIM will be an extension of that for other NASA OSS missions. The detectors will be CCDs with complementary high-resolution imaging calorimeters. This capitalizes on the investments made in detector technology for ASCA, Chandra, and Constellation-X. The optics for MAXIM will evolve from light-weight optical technologies developed for NGST. MAXIM will also leverage off metrology technologies from SIM, TPF, and LISA. Astrometry requirements for MAXIM will be met by technologies pioneered for SIM, TPF, and Gravity Probe-B.

There are several ESA/Japanese missions that have scientific and technical connectivity with MAXIM as well. The ESA mission XEUS utilizes an ambitious formation flying strategy similar to that required for the MAXIM Pathfinder. There is high technical overlap with other ESA missions: DARWIN (the ESA clone of TPF), DIVA, and GAIA (an even higher precision astrometry mission). ESA is also considering the HYPER mission that will make use of a novel atomic interferometer gyroscope, which could be very useful for MAXIM.

The Basic Design and Technology for MAXIM

MAXIM will provide an unprecedented leap forward in spatial resolution. As such, the design is innovative and relies upon modern technologies. Investment in a few key technologies can greatly reduce the cost of the mission through identifying optimal designs and techniques.

The core MAXIM concept is shown in figure 3. It makes use of flat mirrors, which offers two advantages: they are within today's technological grasp, and have comfortable tolerances compared to finite focusing optics. The design also allows us to exploit a significant tolerance advantage due to the forgiving nature of grazing incidence. With reflections at graze angles of

<2 degrees, surface quality and baseline stability tolerances are softened by $1/(\sin\theta)$ or nearly 2 orders of magnitude. This makes the mechanical design of a one microarcsecond X-ray interferometer no more difficult than that of a 100 microarcsecond UV interferometer. The tolerances on mirror figure quality become approximately 2 nm ($\sim\lambda/200$ at λ=6328Å). By a similar argument, our baseline stability is also about 2 nm. The geometry of this design makes our tolerances independent of the baseline dimension. So, an interferometer of this design with a 1-mm baseline will have the same mirror figure and baseline stability requirements as one with a 1-km baseline. We have already demonstrated the basic concept for a 1 mm baseline in the lab, we just need to scale the experiment up. This design also has a large depth of focus, making the range stability of the detector from the optics very loose (10s of meters in our full MAXIM design). We do require good lateral knowledge of the displacement of the detector relative to the source-optics line, but the control is only to the size of the detector. Using a CCD, we can expect detector sizes of nearly a foot by the time MAXIM flies.

Figure 4 shows one concept for MAXIM. Multiple spacecraft, each representing an aperture of the interferometric array, are placed in a circle around a central hub. The X-rays are deflected to another axial craft, which combines the beams and focuses them onto a distant detector. The quality of the image depends upon the number of apertures in the array. Figure 5 shows the effect: with two craft, the image of a point source consists of parallel fringes. As the number of apertures increases the quality of the image increases. By the time 32 apertures is reached, the behavior of the array compares to a telescope with significant diffraction rings. Achieving this behavior is necessary as our targets are variable and we must maintain a constant sampling of the UV plane.

The 32-element interferometer is quite powerful. In Figure 6 we show an image of the solar corona convolved through the "beam pattern" of the MAXIM Pathfinder and randomized to simulate Poisson data. The result is a simulation of an image of Alpha Centauri as it might appear with Pathfinder.

At this early stage, we can still consider modifications to the implementation of the basic design. For example, we are conducting a trade study of focal length versus thermal stability, which could offer a significant loosening of the formation flying tolerances against our baseline design (figure 4). In addition, we are studying the promise of diffraction-limited normal-incidence X-ray optics recently developed for state-of-the-art photo-lithography. We will need to consider the potential advantages of conventional imaging techniques extended to X-ray wavelengths made possible using this existing technology in comparison to the advantages of the grazing incidence approach just described.

Several technologies stand out as needing attention. However, in none of these cases does MAXIM stand alone. The same technologies are being developed for a variety of NASA missions. We can expect to share the burden of technical development.

High Quality Mirrors: MAXIM requires grazing incidence optics to concentrate the beam onto the detector and to create fringes. These mirrors need to have a quality of about $\lambda/200$ (λ=6328Å) if the X-ray wavefront is to be properly maintained. Optics of this quality are fabricated regularly, although they are near the state-of-the-art. For MAXIM, it will be necessary to show that mirrors of this quality can be made in a long skinny geometry and then be mounted and launched into space without distortion. In addition, increasing the inventory from ideal flats to other geometries, such as spheres, would find a place in the development of MAXIM.

Metrology*:* An X-ray interferometer is a sensitive device and must remain stable during operation. Cost effective techniques for thermal and mechanical adjustment and stabilization should be studied for flight and demonstrated in the laboratory to ensure optimal performance in flight.

Pointing: A telescope must point at its target. The very high resolution of the X-ray interferometer requires high pointing stability and information relative to the celestial sphere. Detailed modeling of mission environments coupled with star tracker and gyro and thruster performance indicates the requirements can be met. However, innovative approaches that save substantial cost and complexity may be possible and need to be studied.

Formation Flying: The very long baselines of MAXIM require the use of formation flying. The detector can be hundreds of kilometers from the optic to achieve the needed plate scale. Holding the detector to centimeter precision with knowledge to millimeters at these large distances is a new requirement and needs technical study.

Mission Design and Concept Studies for MAXIM

The first steps of the technical program are already underway using a variety of funding sources including the NASA Institute for Advanced Concepts (NIAC), the Cross Enterprise effort, NASA/GSFC Internal Research and Development (IRAD), and SR&T. Members of our team have conducted a successful laboratory test of the concept behind our baseline design where a 1-mm baseline interferometer produced fringes at 10 angstroms (Cash et al, Nature **407**, 14 September 2000).

NIAC funding extended the concept to 2-D imaging using formation flying as shown in figure 4. The simulation software and concept development was supported at the University of Colorado, and a subcontract to Ball Aerospace has supported the development of an “end-to-end” model. In an effort similar to that performed for NGST, Ball has created software that can simulate all aspects of the mission but is modular in form so that different architectures can be easily tested. The model starts with the layout and includes all sources of error from the components (thermal, mechanical, pointing, optical, etc.) and combines them, inputting into a raytracing system that shows the effects of all the errors combined upon the point response function. This system is just being completed now and will be available for optimization of the mission design within the next couple of months.

Advanced Technology funding from NASA/HQ were used at GSFC’s Integrated Mission Design Center (IMDC) to study the feasibility of the MAXIM Pathfinder mission as shown in figure 7. In this initial IMDC study, all of the optics (and the toughest tolerances) are combined in one spacecraft. A second spacecraft flies in formation with very loose control requirements (meters in range and centimeters in lateral displacement) and carries the detector. The initial estimate of the cost of this mission was $ 1.1 billion, but this price evolved to a lower value as we better defined the detector system from a calorimeter to a CCD array and refined the choice of the attitude determination system.

We are now preparing an alternate pathfinder design that will be only a 1-D imager with the ability to extend the baseline beyond 1-2 meters upward to 100s of meters. This design will capitalize on technologies developed for the “Starlight” mission. While we have not completed a full integrated mission study for this option, we expect that it will cost much less- comparable in cost to the Origins technology demonstration mission Starlight (formally called ST-3). Both the original MAXIM Pathfinder design and this alternate approach offer exciting, though different, scientific capabilities.

GSFC/IRAD funding is now supporting an X-ray interferometer test-bed to better define tolerances for interferometer missions. SR&T funding is supporting a Colorado University interferometer where advanced concepts in fringe magnification will be tested. Laboratory work on mirrors and techniques for alignment and phase closure is starting to address the optical requirements, but this needs support at a higher level if risk and costs for MAXIM are to be reduced. Engineering studies using integrated design modeling tools are allowing mission system level designs to be quantitatively studied – the only way that flight performance of new missions can be realistically assessed prior to launch. We are now formulating a detailed technology roadmap with tie-ins to the NASA Technology Inventory.

Collaboration with Universities, Industry, and Foreign Partners

Currently, the MAXIM study involves efforts from several universities, NASA/GSFC, NASA/MSFC, JPL, some small businesses (through SBIR), and a few major aerospace firms. Participants are currently from the United States, though we envision that an international collaboration will occur. The core MAXIM science team is listed in Table 2.

Table 2: The MAXIM Study Team

Team Member	Institution
Dave Burrows	Penn State
Webster Cash	University of Colorado
Martin Elvis	CFA
Keith Kroening	TRW
Keith Gendreau	NASA/GSFC
Marshall Joy	NASA/MSFC
Steve Kahn	Columbia University
Keith Kroening	TRW
Shri Kulkarni	Cal Tech
Chris Martin	Cal Tech
Rob Petre	NASA/GSFC
Jim Phillips	SAO
Chris Reynolds	University of Maryland and NASA/GSFC
Mark Schattenburg	MIT
Herman Marshall	MIT
Mike Shao	JPL
Marty Weisskopf	NASA/MSFC
Nicholas White	NASA/GSFC
David Windt	Columbia University
Will Zhang	NASA/GSFC

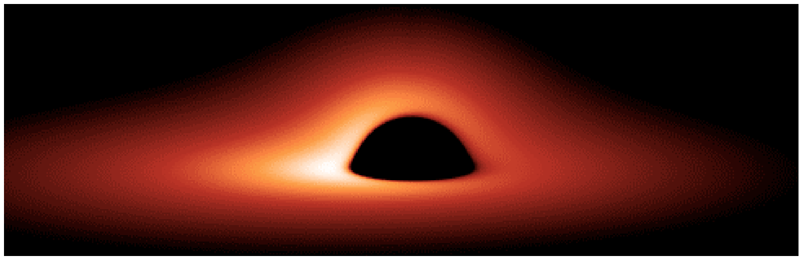

Figure 1: A simulation of the x-rays from the accretion disk and black hole at the center of NGC 4258, by Chris Reynolds. The top of the picture is actually an image of the accretion disk on the far side of the black hole distorted by the intense gravitational field.

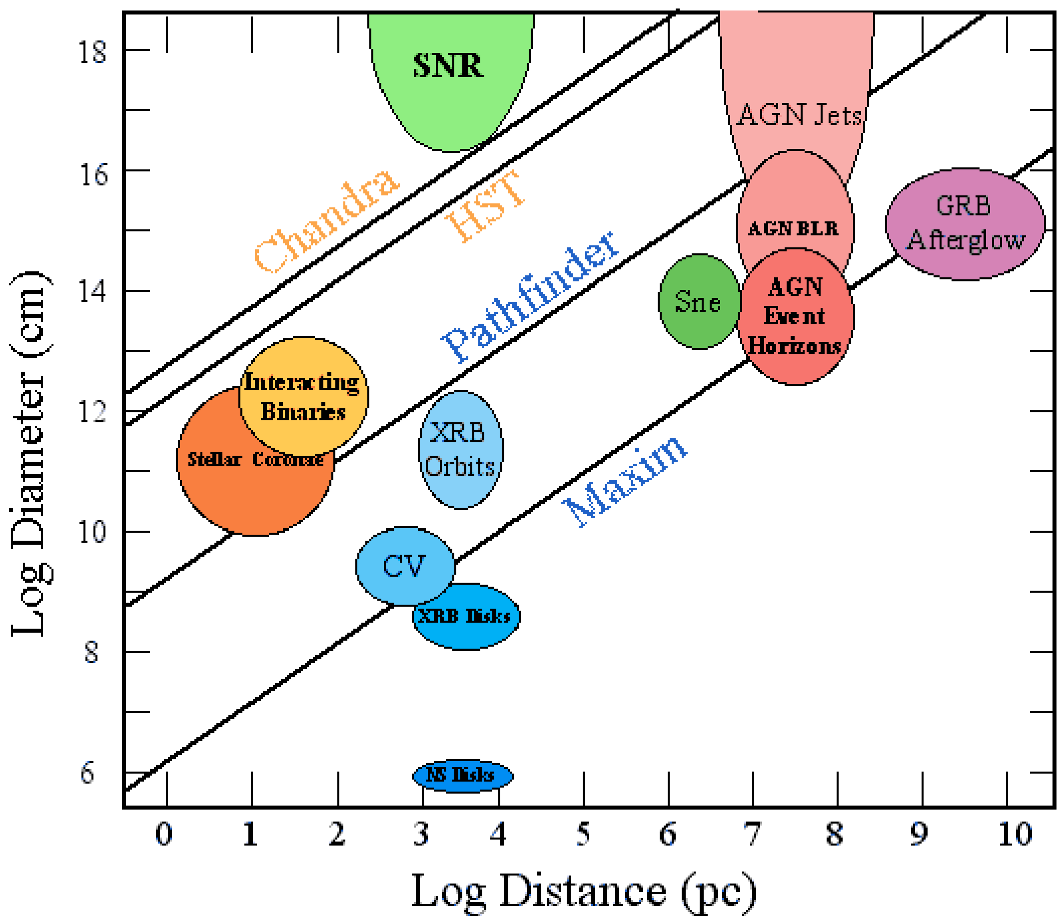

Figure 2: The angular sizes of astrophysical objects compared to the resolution of various telescopes. The Chandra and HST resolutions are 0.5 and 0.1 arcseconds, respectively. The MAXIM resolution is 0.1 micro-arcseconds. MAXIM will be able to leap the gap from supernova remnants and the outer parts of jets to observing binaries, stellar coronae, accretion disks and even event horizons.

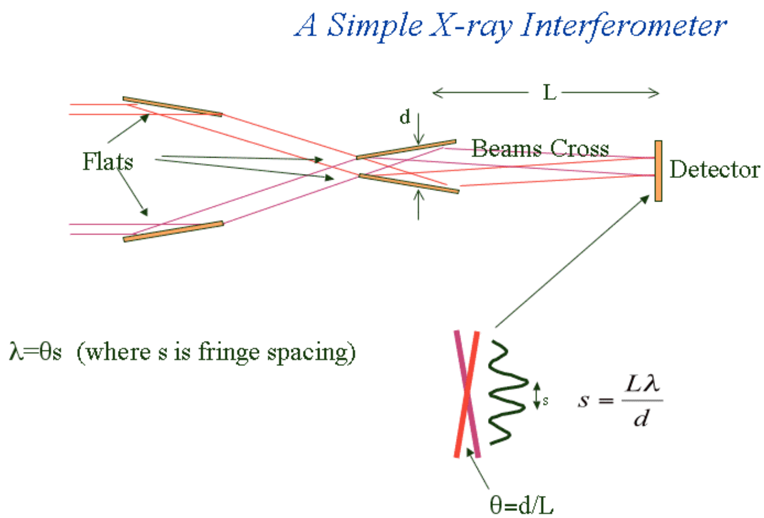

Figure 3: The basic concept behind the MAXIM X-ray interferometer. In this 1-D figure, we show two channels. Flat primary mirrors capture these rays and direct them to flat secondaries which act as combiners. The secondaries direct the rays to interfere at a distance, L, away on a detector. The design capitalizes on grazing incidence which loosens the surface and baseline tolerances to a level comparable to a UV interferometer.

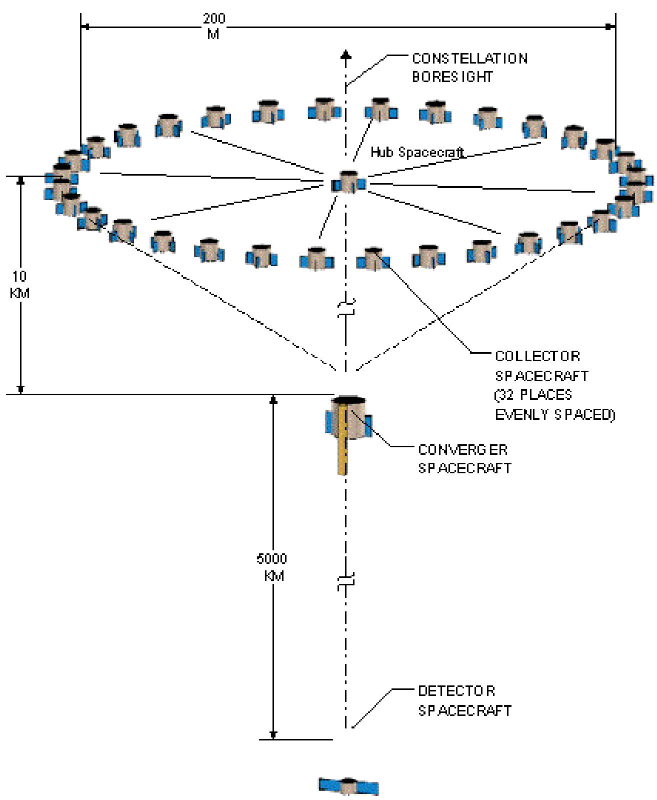

Figure 4: The baseline implementation of the basic MAXIM X-ray interferometer design. Here the primary mirrors (32) are distributed amongst individual spacecraft flying in formation in a ring. A hub spacecraft provides a fiducial to maintain the precision of the formation flying. 32 secondary mirrors are arranged in a ring with in a converger spacecraft which directs the various channels to a detector spacecraft 5000 km away. The formation flying of the primary mirrors relative to the converger spacecraft has a tolerance of nanometers, while the depth of focus allows us to have looser control (centimeters to meters) of the detector spacecraft.

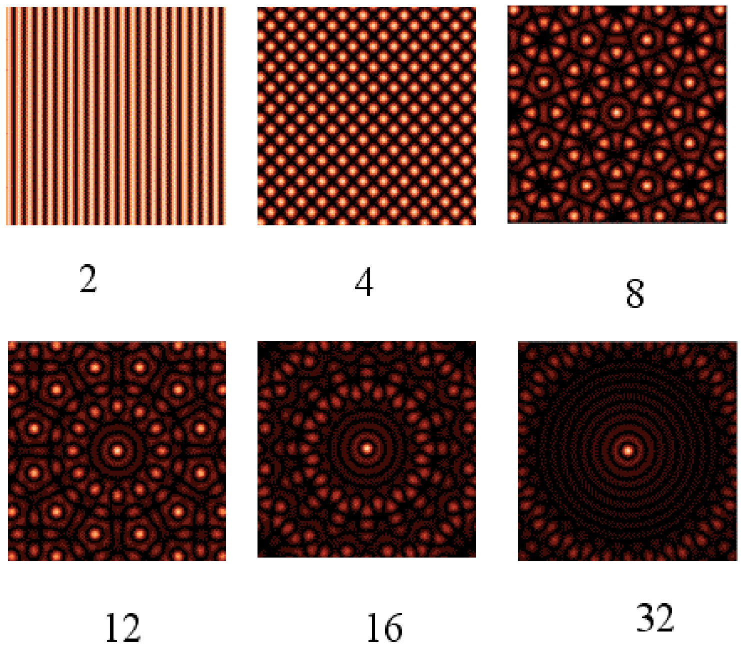

Figure 5: The image of a point source using different numbers of interferometric channels in our baseline design. The first image uses two channels just as shown in our 1-D baseline design (figure 3). As we add more of these pairs of channels about the azimuth, we go beyond 1-d imaging and into two dimensions. As the number of channels approaches 32, we see a well resolved point

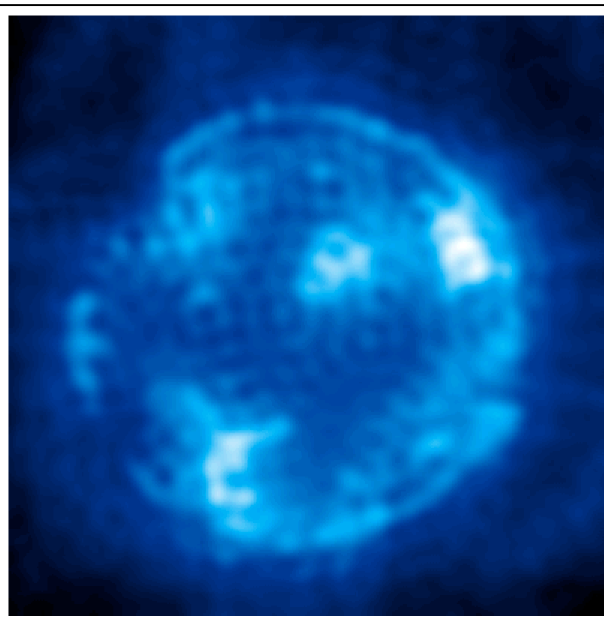

Figure 6: Simulated data from MAXIM Pathfinder.
We see an image that approximates the appearance of the corona of Alpha Centauri A taken with MAXIM Pathfinder. The simulation includes the beam pattern of the interferometer and the Poisson statistics at the expected level of signal.

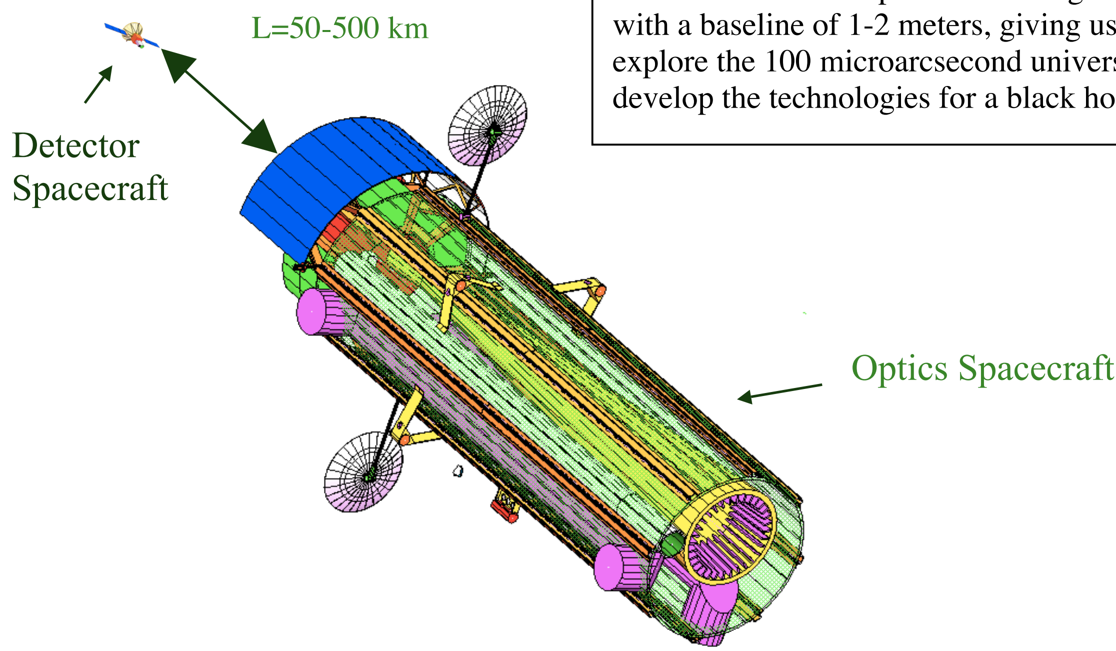

Figure 7: GSFC IMDC study concept for the MAXIM Pathfinder Mission. One Spacecraft contains all of the optics, while a second spacecraft flies 50-500 km away with the focal plane detector. Both spacecraft fit into a Delta IV launch vehicle. This mission allows us to test the interferometer concepts shown in figures 3 and 4 with a baseline of 1-2 meters, giving us a way to explore the 100 microarcsecond universe and develop the technologies for a black hole imager.